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Progress in electronics and photonics with nanomaterials

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ABSTRACT

Nanomaterials have been at the center of attraction for almost five decades as their contributions to different disciplines such as electronics, photonics and medicine are enormous. Various kinds of nanomaterials have been developed and are currently utilized in innumerable applications. Nevertheless, their simple realization and easy and efficient upscaling are topics under intense investigation. Innovative strategies have been adopted for nanomaterial synthesis and their usability. Here, we provide a brief overview on nanomaterials ranging from basic understanding of their structure-property relationship to advanced applications. This editorial covers various aspects about nanomaterials, which will be useful/attractive for beginners in the field of nanotechnology as well as for experts and for industrialists looking forward to exploit them for real world applications.

The term nanotechnology refers to the science and technology of materials with dimensions on the order of 10^{-9} m, and it can be traced back to the prestigious lecture by Richard Feynman [1,2] during the 1960's. Nevertheless, materials with such dimensions have been used since ancient times. For example, drinkable gold [3] and zinc ash [4], which contain a form of nanoscopic material, were used more than 2000 years ago in medical applications. After the word *nano* was coined, the field has witnessed rapid progress. A careful literature search from Web of Science suggests that almost 150,000 articles with 'nano' as topic and >52,000 papers with 'nano' as a word in the title have already been published, indicating an intense research focus. Moreover, the provided numbers should be considered only as the lowest estimates, since the database only reaches back to 1945 and does not contain all scientific literature. At the beginning, the progress was driven by independent research in various disciplines. This changed in the 21st century, during which nanotechnology has emerged as an interdisciplinary subject. The initial phase witnessed the main focus on synthesis of various nanomaterials by different techniques and their adequate chacterizations for establishing the structure-property relations. In last couple of years, the scope of the applications has significantly widened and includes water treatment, cosmetics, energy and healthcare sectors. In this way, nanotechnology has entered the society through various day-to-day appliances.

The initial criterion for length scales of nanomaterials (at least one dimension should of length between 1 and 100 nm) has loosened over time. The typical definition today rests rather on structural compatibilities and utilization simplicities in a form where nanoscale features are easily accessible for desired applications. However, especially the surface-to-volume ratio and quantum confinement phenomenon are still major criteria for defining nanoscale materials. Most of the extraordinary physical and chemical properties (such as chemical reactivity, absorption, emission and biological mobility) are introduced when the material dimensions approach the de Broglie wavelength, although the actual limiting size of course varies for different materials. Nevertheless, at these very small length scales, all the material classes (e.g., metallic, semiconductors, insulators and inorganic, carbons, organic polymers) display exotic electronic properties which leads to novel applications in the fields of nanoparticle sensitized solar cells and biomedical imaging.

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Nanomaterials have played a key role in advancing electronics and photonics. Many devices based on nanoscale materials are already in daily use, for example in the field of optoelectronics [5–8], solar cells [9–11], and energy related applications [12]. Nanomedicine is an upcoming front where these nanoscale materials are also expected to take a lead role in the applications such as biomedical imaging and drug delivery [13–18]. In particular, nanoparticles and ligated nanoparticles are currently used for selective imaging of tumor cells through fluorescence spectroscopy and MRI technique and for selectively delivering drugs to specific cells [19,20]. Many applications have already been the center of focus for researchers from different disciplines, while many are yet to be realized. It is practically impossible to list all different nanostructures and their applications, but Fig. 1 provides some general categories of nanostructured materials (bottom portion) and their various advanced applications (upper portion).

Due to the large number of possible applications, nanomaterials remain an intense research topic with continuous advances occurring at fast pace. Despite the rapid progress achieved over the past decades, the basic questions nevertheless remain the same: what are the best synthesis strategies for each type of a nanostructure, and what are the exploitable structure-property relationships? Different synthesis techniques deliver different respective forms of nanomaterials with varying features constantly opening new questions to be answered on our path to the complete fundamental understandings. Fig. 2 describes the general strategy of the synthesis of nanostructured materials and their understanding in terms of their physical, chemical and other properties. One way to classify nanoscale materials is to divide them based on the number of nonrestricted dimensionalities into 0D, 1D and 2D materials. This highlights in how many dimensions the confined properties are restricted (the rest of the dimensions are decreased below the de Broglie wavelength limit). Many innovative strategies have been adopted for synthesizing nanostructured materials from inorganic, organic, carbon and polymeric materials in different forms. Although pure form of nanomaterials already exhibit interesting features, to enhance their functionalities they can also be hybridized with other materials as composites for desired applications. The synthesized nanomaterials are often characterized with various experimental techniques towards assessment of their different properties (right panel in outer circle in Fig. 2) and to find a better structure-property co-relations, often analytical and simulation studies (left panel in outer circle in Fig. 2) are performed. Computational modeling approaches have evolved as complementary tools to experimental methods for characterization of structure and properties of nanomaterials and for establishing the structure-property relationship. Based on the experimental conditions, the theoretical results provide detailed insights about involved nanomaterials and accordingly can predict their suitability for technological applications.

It is important to mention that, although conventional approaches have been very successful towards synthesis of nanomaterials, they often fail to meet the technological requirements for applications, especially towards electronics and photonics. This is because the microscopically small structures need to be interfaced with external connections to access their properties. This often involves complicated processing steps, e.g., clean room integrations, which increase the overall cost. Such integration challenges have forced the materials community to think further, which resulted in several unconventional innovative strategies for the efficient utilization of nanomaterials [21–26]. To overcome the integration challenges, even a new form of nanostructured materials, so-called 3D nanomaterials, has been created. 3D nanomaterials are macroscopic networks built out of 1D nanoscopic building blocks, which on one hand are free from

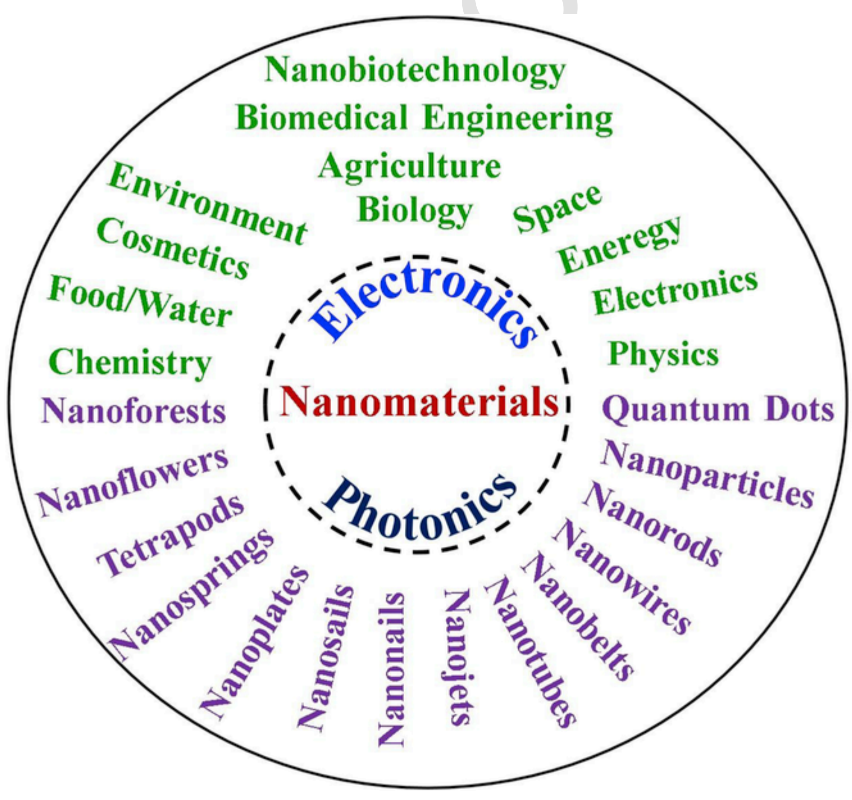

Fig. 1. Overview of nanoscale materials for electronics and photonics: Different morphologies are listed at the bottom, while the upper part lists their possible application fields in various disciplines.

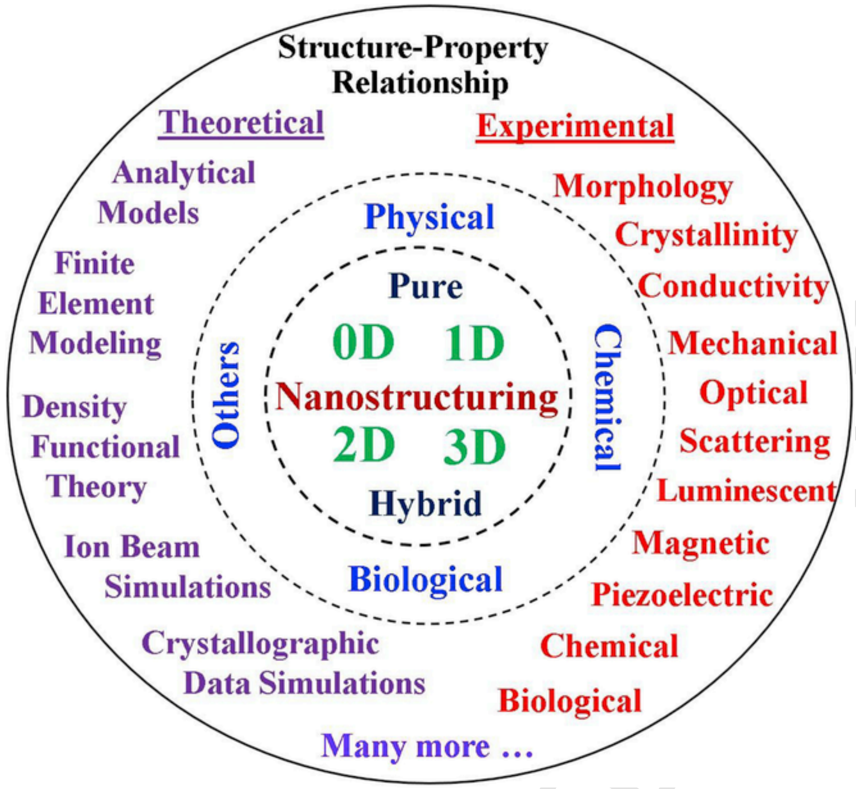

Fig. 2. Basic steps followed by the research community for synthesis, characterizations, simulations, etc., towards understanding their detailed structure-property relationships.

nanoscale utilization barriers, but on the other hand offer easy accessibility to necessary nanoscale features at large dimensions [27–29]. These 3D nanomaterials are interesting in terms of the fundamental structure-property relationship and also have the potential to revolutionize the modern technology. This has brought them to the main research stream at the moment. 3D nanomaterials in the form of porous cellular solids can be synthesized by conventional physical and chemical methods, involving top-down and templates-based strategies. The recent development in complex nanostructures, such as tetrapods and multipods, have also opened new avenues towards 3D nanostructuring in terms of fabrication of highly porous and flexible interconnected ceramic networks for advanced applications. [30,31]. These networks can be directly utilized for various technological applications or used as sacrificial templates for fabricating new 3D porous nanomaterials from inorganic materials and carbons [32–38]. These 3D nanomaterials have thus opened a new direction towards fundamental research and technological applications.

In general, nanoscale materials offer unique opportunities for developing our society, for example, for improving our fundamental knowledge and for providing high performance technological appliances (electronics and photonic devices) that make life simpler and subsequently better by releasing human resources from physically demanding laborious tasks. The field is witnessing new innovations every day, which allows it to remain interesting and vivid. In our view, there remains much to be realized. This special issue from the European Materials Research Society (EMRS)-Fall17 meeting presents a brief overview about fundamental progress in the direction of synthesis of semiconductor and many other nanomaterials towards electronics and photonics and various advance applications. The special issue starts with a nice and detailed review article on ‘A Lifetime of Contributions to the World of Semiconductors Using the Czochralski Invention’ by Prof. Manijeh Razeghi (Northwestern University, USA), which presents a brief overview about the development of semiconductor materials from scratch to modern advanced optoelectronic technologies. Furthermore, the special issue contributions cover a broad scope towards (i) data storage, (ii) 0D, 1d, 2D and 3D nanomaterial growth, (iii) oxide materials and nanosensing devices, (iv) plasmonics, photonics and photovoltaics, (v) advanced nanocomposites, (vi) biomaterials, (vii) photocatalysis and water purification, (viii) ceramics and wood composites, (ix) phosphors and carbon materials, and (x) theoretical studies on several nanomaterials' growth, properties and applications. The papers are very detailed with a lot of information and we hope that they will be of high interest for broader research community.

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